ULTRAMAFIC AND GABBROIC NODULES FROM THE BULLENMERRI AND GNOTUK MAARS, CAMPERDOWN, VICTORIA

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ABSTRACT: A diverse assemblage of well preserved ultramafic blocks is described from agglomerates around Lakes Bullenmerri and Gnotuk. They were ejected during initial maar eruptions of nepheline basanite magma south-west of Camperdown late in the Quaternary. Nodules include metaperidotites, metapyroxenites, peridotites, pyroxenites, hornblendite and essexite. Contacts in nodules establish relationships between different rock types. The metamorphic nodules show textures such as curved crystal lamellae, recrystallisation and mylonitisation. Their mineralogy indicates an upper mantle origin, with metapyroxenites forming lenticular bodies within predominant lherzolites. Some metamorphic nodules show evidence of hybridisation and Mg-depletion due to local partial melting. The resultant liquids yielded the clinopyroxene and olivine cumulates, which show increased Ti and Fe. A similar, more hydrous magma may have formed the intrusive hornblendite which occupies fissures that cut all the other rocks except the essexites.

INTRODUCTION

The limited denudation of the tuff rims around Lakes Bullenmerri and Gnotuk suggests that maar-producing volcanism ceased there in late Quaternary times. The shapes of the lake-filled depressions indicate that several related eruption centres were involved. Bedded tuffs and agglomerates similar to those seen in other local maars such as Elingamite, Purrumbete and Keilambete are well exposed around the lakes and at many points they are seen resting on Miocene marine sediments. In most places tuffs dip at 35° to 50° inwards, towards the eruption centres. The basal few metres of tuffs and agglomerates abound in ultramafic nodules of remarkable variety, up to 12kg in weight and 30 cm diameter. These are associated with large blocks of basalt and gabbro, some weighing several tonnes and exceeding 2 m diameter. Beach sands are composed largely of fresh olivine, pyroxenes, amphiboles and scattered garnet with rarer spinel, ilmenite and anorthoclase.

Spinel lherzolite and pyroxenite nodules occur almost to the exclusion of other ultramafic rocks at most Western District localities (e.g. Mt. Shadwell, Mt. Leura, Mt. Noorat). By contrast the assemblages at Lakes Bullenmerri and Gnotuk show a predominance of nodule types that are extremely rare elsewhere. Most notable are garnet and spinel pyroxenites, olivine and amphibole-bearing hybridised garnet pyroxenites, amphibole peridotites and rare mica peridotites. Some nodules are mylonitised. These rocks lack plagioclase, in contrast to the garnet-plagioclase-pyroxene rocks from The Anakies and Mt. Franklin (Wass & Irving 1976).

Grayson & Mahony (1910) first described the geology of Lakes Bullenmerri and Gnotuk in detail, describing their characteristic rock types. They noted an isolated fine-grained garnet pyroxenite nodule and recorded garnet in the beach sands. Thin sections of essexite nodules were figured. Ellis (1976) examined the relationship between deep-seated blocks and their host lavas at Bullenmerri and elsewhere. He recorded a wide range of inclusions associated with the nepheline basanite but no garnet-bearing nodules. Aspects of the general geology of the maars are recorded by Gregory (1904), Ollier & Joyce (1969, 1973), Gill (1964) and Joyce & Evans (1976).

Nodules vary from angular, impact-spalled fragments and joint blocks to types having one or more smooth, rounded surfaces. Some garnet pyroxenites show garnets eroded into smooth, concave pits on rounded surfaces. Alteration of the nodules is minimal although most garnets have a thin margin of grey, fibrous 'kelyphite' (a fine-grained intergrowth of spinel, orthopyroxene and

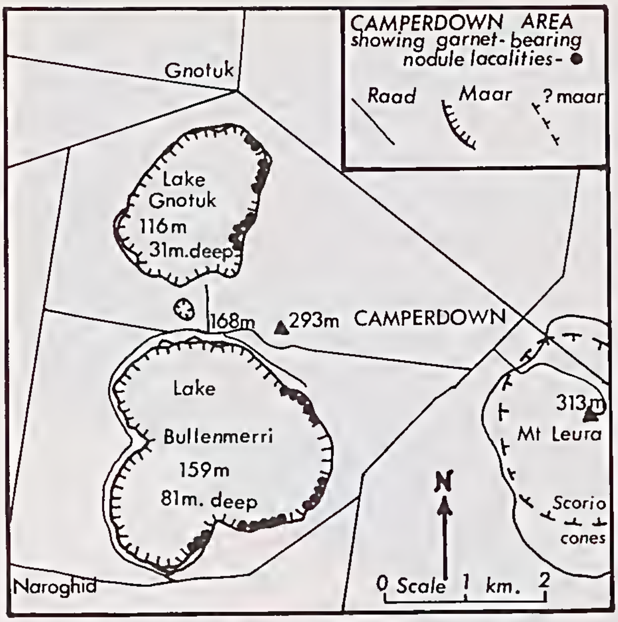


FIG. 1—Locality map of Camperdown area.

plagioclase pseudomorphing the garnet). Garnet-bearing ejected blocks are common along the eastern shores of both lakes (Fig. 1) where the lower agglomeratic tuff horizons intersect the shore. None have been found on the western shorelines. Other ultramafic blocks show a similar distribution, although isolated examples are found along the western shores. Xenoliths of country rocks include Tertiary mudstones, marls and limestones which are largely unaltered, although some have been baked.

An outcrop of nepheline basanite circling Lake Gnotuk and part of Bullenmerri may have been a flow from Mt. Leura, predating the maar eruptions. It contains many ultramafic nodules but no garnet-bearing types were seen. The small amount of basanitic lava adhering to a few nodules from the tuffs contains abundant xenocrysts of olivine, amphiboles and pyroxenes set in a glassy groundmass.

This paper describes the field aspects of the Bullenmerri-Gnotuk nodules. The assemblage is unique in Australia and the locality should be of international significance when detailed geochemical work has been carried out.

CLASSIFICATION OF NODULES

The complexity of the rocks comprising the nodule assemblage makes their classification extremely difficult (Table 1). As well as distinctive mineralogy, mixing, metamorphic, igneous and cumulate textures are recognisable in most rocks. Other specimens show contacts between different

TABLE 1

CLASSIFICATION OF ULTRAMAFIC AND GABBROIC NODULES FROM BULLINMERRI AND GNOTUK

A. METAPERIDOTITE GROUP	
1. Garnet Sub-group—Not represented	
2. Spinel Sub-group	
Harzburgite	V
Enstatite + Cr diopside ± spinel lherzolite	C
Phlogopite + Cr diopside ± spinel ± enstatite lherzolite	V
3. Feldspar Sub-group—Not represented	
4. Mg-depleted Sub-group	
Mylonitised and fused lherzolites	O
Amphibole + Cr diopside ± spinel lherzolite. Kaersutite ovoids, some with spinel cores and Cr diopside mantles	A
Cr diopside ± spinel peridotite to dunite	S
B. Metapyroxenite Group	
1. Primary Sub-group	
Primary garnet pyroxenite. Coarse orange to pink garnet, green clinopyroxene, minor orthopyroxene and spinel	S
Coarse spinel pyroxenite. Large green clinopyroxene with orthopyroxene lamellae. Large black spinel	R
2. Garnet exsolution Sub-group	
Transitional spinel-garnet pyroxenite. Spinel with garnet mantles and orthopyroxene lamellae in relict clinopyroxene replaced by garnet	O
Exsolved garnet pyroxenite	O
3. Hybridised Sub-group	
Complex hybridised pyroxenites ± spinel, olivine, garnet, kaersutite, Cr diopside, enstatite and xenocrysts from other groups	C
C. Peridotite-Pyroxenite Group	
1. Magmatic Sub-group	
Complex hybridised peridotites ± kaersutite and xenoliths of A2, B1 & C2 Sub-groups	O
Augite peridotite (wehrlite)	O
Augite clinopyroxenite	O
Orthopyroxene + clinopyroxene pyroxenite (websterite)	S
2. Cumulus Sub-group	
Amphibole peridotite. Olivine with amphibole intercumulus	C
Clinopyroxene peridotite. Olivine with clinopyroxene intercumulus	O
Amphibole clinopyroxenite. Clinopyroxene with amphibole intercumulus ± biotite	S
D. Hornblendite-Essexite Group	
1. Hornblendite Sub-group	
Hornblendite ± clinopyroxene, biotite & ilmenite	C
2. Essexite Sub-group	
Alkali gabbro (essexite)	A

A—abundant; S—sparse; C—common; R—rare; O—occasional; V—very rare phases, indicating relationships. Grouping is based on these factors, in addition to petrographic assessment and electron microprobe analyses of constituent minerals (Tables 2 to 4). The assemblage is significant due to the general absence of feldspars and the predominance of amphibole peridotites. Interpretation of rock type origins and comparisons with other nodule localities are made with reference to recent literature.

Metaperidotites

Enstatite—Cr diopside—spinel lherzolites predominate at most nodule localities, having olivine of Fo_{87-92} (Frey & Green 1974), enstatite of Mg_{90} and accessory pleonaste to picotite with 1 to 2% Cr_2O_3. Similar nodules are common at Lakes Bullenmerri and Gnotuk, but amphibole peridotites predominate. Amphibole is very rare at the numerous other eruption centres around Camperdown.

The amphibole peridotites have olivine of Fo_{82-88} and little or no enstatite. In hand specimen, amphiboles (predominantly kaersutites) range from light fawn and olive-brown to almost black. The virtual absence of orthopyroxene and Mg-depletion of the olivine may be due to Mg substituting into the development of amphibole. When compared with those of the hornblendites, the peridotite amphiboles are lower in Ti and higher in Al, a feature identified with high-pressure amphiboles by Best (1974). Amphibole compositions and the presence of orthopyroxene in some nodules indicates origins in the upper mantle (Green, 1973). Amphibole occurs either as individual crystals or as ovoid, interlocking patches. Orientation of the patches often produces a distinct banding in the peridotites, which may in turn be intersected by planes of finer, granular amphibole (Fig. 4, Bm114). Bright green Cr diopside appears as quite large, irregular patches or scattered crystals within the olivine matrix and often forms broad mantles around the amphiboles. Thin bands of Cr diopside-rich peridotite run parallel to the amphibole lineation in some nodules. A few amphiboles have spinel cores. The amphibole peridotites probably represent the results of partial melting in the upper mantle lherzolites under wet conditions (Vinx & Jung 1977). Amphiboles similar to those from Bullenmerri are recorded from nodules in the Westeifel maars (Becker 1977).

Mylonitised peridotites are not uncommon at Bullenmerri, showing a semi-foliated, sugary texture with finely granular olivine (Fo_{75-85}). Cr diopside and amphiboles are drawn out into augen and shard-like forms, often with interstitial glass. The metaperidotites are frequently intruded by hornblendite, which is rich in reddish-brown biotite in the reaction zones adjoining wall rock. Occa-

Table 2

Electron Microprobe Analyses of Pyroxenes in Nodules from Bullenmerri and Gnotuk

	CLINOPYROXENES						ORTHOPYROXENES			
Phase	A4	B2	B2	B3	B3+C1	C2	B1	B2	B3	B3+C1
Specimen	Gn151	Bm116	Bm20	Bm55	Bm92	Bm83	Gn168	Bm153	Bm55	Bm92
SiO_2	51.44	52.11	52.20	51.41	50.70	51.11	53.42	54.43	57.87	51.33
TiO_2	.78	.59	.36	.66	1.67	1.50	.07	.20	.13	.87
Al_2O_3	5.74	5.60	7.22	6.32	7.78	8.10	4.11	4.15	4.68	8.04
FeO*	5.66	4.83	4.12	3.59	7.39	7.10	11.67	11.60	5.53	13.73
MnO	.09	.13	.05	.07	.12	.16	.24	.18	.15	.25
MgO	15.72	14.55	13.59	14.52	12.72	12.75	28.85	29.94	31.30	24.02
CaO	18.72	21.67	21.14	21.85	18.58	18.10	.54	.70	.44	1.76
Na_2O	1.29	.83	1.25	1.14	1.68	1.74	.04	.02	.08	.13
K_2O	0	0	0	.01	0	0	0	0	.02	0
Cr_2O_3	.24	.05	.16	.24	.03	.03	.11	.04	.21	0
NiO	.03	0	.01	.07	.08	.08	.01	.09	.10	.07
Total	99.51	100.36	100.10	99.88	100.74	100.67	99.06	100.84	100.51	100.20
Ion%										
Mg	48.9	44.3	43.7	45.0	42.1	42.8	80.6	81.0	90.2	72.8
Fe	9.9	8.3	7.4	6.2	13.7	13.4	18.3	17.6	8.9	23.4
Ca	41.2	47.4	48.9	48.8	44.2	43.8	1.1	1.4	0.9	3.8

* Total iron as FeO (Fe^{++}).

TABLE 3

ELECTRON MICROPROBE ANALYSES OF GARNETS AND OLIVINES IN NODULES FROM BULLENMERRI AND GNOTUK

	GARNETS					OLIVINES			
Phase	B1	B2	B3	B3	B3+C1	A2	A4	C1	C2
Specimen	Bm20	Bm122	Bm103	Gn8	Bm92	Bm179	Bm129	Bm108	Bm103
SiO_2	42.71	41.29	41.65	40.91	42.09	40.87	39.26	39.49	38.59
TiO_2	.12	.03	.10	.05	.38	0	0	.05	.01
Al_2O_3	22.70	22.78	22.91	23.14	22.03	.02	.03	.01	.02
FeO*	11.42	13.67	12.89	13.85	14.79	8.96	12.63	16.57	22.55
MnO	.23	.56	.40	.57	.32	.06	.21	.15	.15
MgO	16.54	15.65	16.70	16.18	14.98	49.50	46.73	42.42	37.94
CaO	6.28	5.77	5.70	5.73	5.45	.05	.05	.06	.10
Na_2O	.01	.03	.06	.03	.01	.01	0	.05	.01
K_2O	0	0	.01	.01	.01	.01	.01	0	0
Cr_2O_3	.24	.13	.08	.13	.12	0	0	.03	.06
NiO	.02	.08	.11	.07	.08	.31	.42	.25	.22
BaO	0	0	.14	.14	.12	0	0	.09	.11
Total	100.27	99.99	100.75	100.81	100.38	99.79	99.34	99.17	99.86
Ion%									
Mg	60.2	57.0	59.6	58.4	55.1	90.8	86.8	82.0	75.0
Fe	23.4	27.9	25.8	28.0	30.5	9.2	13.2	18.0	25.0
Ca	16.4	15.1	14.6	13.6	14.4	—	—	—	—

* Total iron as FeO (Fe^{++}).

sionally, thin partings are lined with biotite which is deep green in hand specimen and amphibole is absent. Contacts between metaperidotites and pyroxenites of the peridotite-pyroxenite group are sharp and planar, a feature also noted by Irving (1974a) and Wilshire & Shervais (1976).

METAPYROXENITES

The metapyroxenite group comprises nodules of up to 5 kg which contain spinel and/or garnet. They range from simple, equigranular, homogeneous types, through a series of exsolution phases to complex multi-phase varieties with olivine, amphibole and Cr diopside. The latter are profoundly disrupted, hybridised rocks containing xenocrysts with curved lamellae, rare schlieren from metaperidotite phases and minerals showing a wider range of compositions. Nodules typically contain pyrope-rich garnet as pink to orange-red anhedral crystals averaging 3 mm diameter, but up to 25 mm in rare cases. Analyses of the garnets (Table 3) show molecular percentages in the range $Py_{57-60}Alm_{23-28}Spe_{14-16}$. The pyrope proportion is significantly higher than in amphibole and feldspar-bearing pyroxenites from the Anakies (Irving 1974a), Gloucester (Wilkinson 1974), Delegate (Lovering & White 1969, Irving 1974b) and Ruby Hill (Lovering 1964). There is a marked similarity to garnet compositions of feldspar-free pyroxenites from Delegate, Mt. Leura and Mt. Shadwell (op. cit.), Table Cape (Sutherland 1979) and Salt Lake Crater, Oahu (Wilkinson 1976). Comparative analyses are plotted in Fig. 2. Mg content is lower than for most eclogite (griquaite) nodules from South African kimberlites (Nixon 1973) and Siberian kimberlites (Frantsesson 1969). No compositional differences were detected between large garnet grains and exsolved garnet lamellae within large clinopyroxenes.

Clinopyroxenes range from light grey-green and rich emerald green to black in hand specimens. Their composition varies from salite and augite to diopside (Table 2). Clinopyroxene compositions from garnet pyroxenite nodules near Delegate are closely comparable (Lovering & White 1969, Irving 1974b). Orthopyroxenes lie in the En_{72-90} range with alumina rising from 4% in the enstatites to around 8% in the bronzites. Except in garnet pyroxenites showing evidence of hybridisation, orthopyroxene is normally absent as distinct grains. Unaltered large clinopyroxenes have lamellae near bronzite in composition, although these are often replaced by garnet. Spinels are aluminous with most having compositions in the pleonaste-picotite range. Their Cr_2O_3 content (0.6 to 2.7%) is lower than that of typical kimberlitic spinels (Frantsesson 1969).

The presence of sporadic, patchy olivine around Fo_{85} and deep greenish-brown kaersutite in the hybridised metapyroxenites suggests a link with

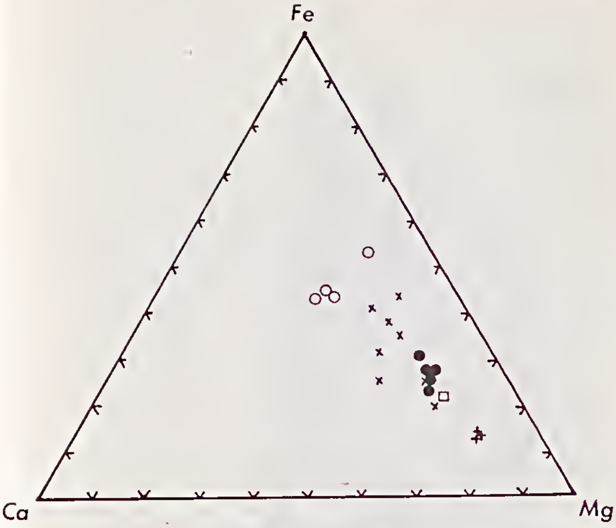


FIG. 2—GARNETS. Ternary diagram comparing ionic proportions of Ca, Mg, and Fe in garnets from Bullenmerri (black circles) with those from garnet lherzolite, Bow Hills, Tas (+) (F. L. Sutherland, unpubl. data); metapyroxenites, Salt Lake Crater, Oahu (square) (Wilkinson 1976); metapyroxenites and plagioclase pyroxenites, Delegate, N.S.W. (x) (Lovering & White 1976) and plagioclase pyroxenites, Gloucester, N.S.W. (o) (Wilkinson 1974).

the amphibole peridotites. Nodules showing the assemblage clinopyroxene + orthopyroxene + garnet + spinel + kaersutite + olivine show great variation in texture and composition, with even small specimens showing up to four distinct mineral assemblages (Bm 98). One of the rocks is garnet lherzolite which if found in isolation from the other rocks resembles higher pressure mantle material. Garnet compositions are identical to those in the olivine-free pyroxenites, which with their textural similarity suggest that the lherzolite is a hybrid phase resulting from mixing and exsolution reactions.

Banding is frequently seen in the metapyroxenites and boundaries are generally planar except for the hybridised varieties which show irregular contacts. Examples of textures and boundary relationships between rock types are given in Fig. 4.

Nodules comparable with the rare plagioclase-free spinel pyroxenites (websterites) of Delegate are much more common at Lakes Bullenmerri and Gnotuk, where plagioclase-bearing phases have not been found. Many examples show an exsolution reaction series yielding garnet as described by Green (1966), Lovering & White (1969) and Irving (1974b). This shows, under subsolidus cooling conditions, aluminous clinopyroxene exsolving garnet, some orthopyroxene and minor spinel. At the same time, spinel reacts with clinopyroxene to produce additional garnet. Fig. 5 gives examples of textures displayed by nodules illustrating the clinopyroxene + spinel reactions. The spinel pyroxenite specimen Gn 36 is garnet-free with anhedral to subhedral black spinels up to 9 mm and greyish-green clinopyroxenes up to 40 mm long having thin orthopyroxene lamellae spaced at intervals of 0.05 to 1 mm. Minor granular orthopyroxene is present along irregular channels with fine spinel and granular clinopyroxene, perhaps reflecting zones of partial melting. This garnet-free stage is rare. Normally spinels have developed mantles of granular garnet which are clearly visible in Bm 67, although the orthopyroxene lamellae in the clinopyroxene often remain. Bm 62 shows spinels that have been largely expended to form large, granular patches of garnet; whilst all the orthopyroxene lamellae are replaced by garnet in thin plates or blebs. Bm 57 shows granular garnet with little remaining of the former lamellar arrangement. Spinel is present only as isolated relict patches and there are sometimes small transparent brown grains of orthopyroxene.

Considerable experimental data exist for similar groups of nodules from Delegate (op. cit.) and Salt Lake Crater (Beeson & Jackson 1970). Such rocks have optimum conditions of formation in a dry state at a pressure range of 13 to 17 kb

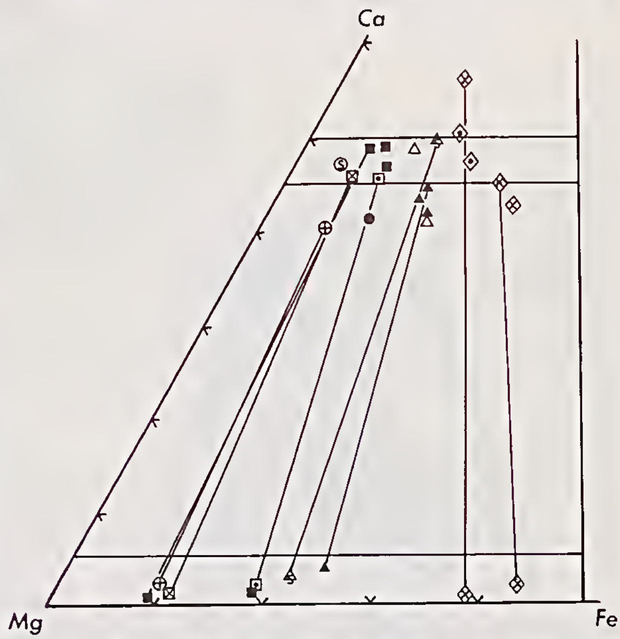
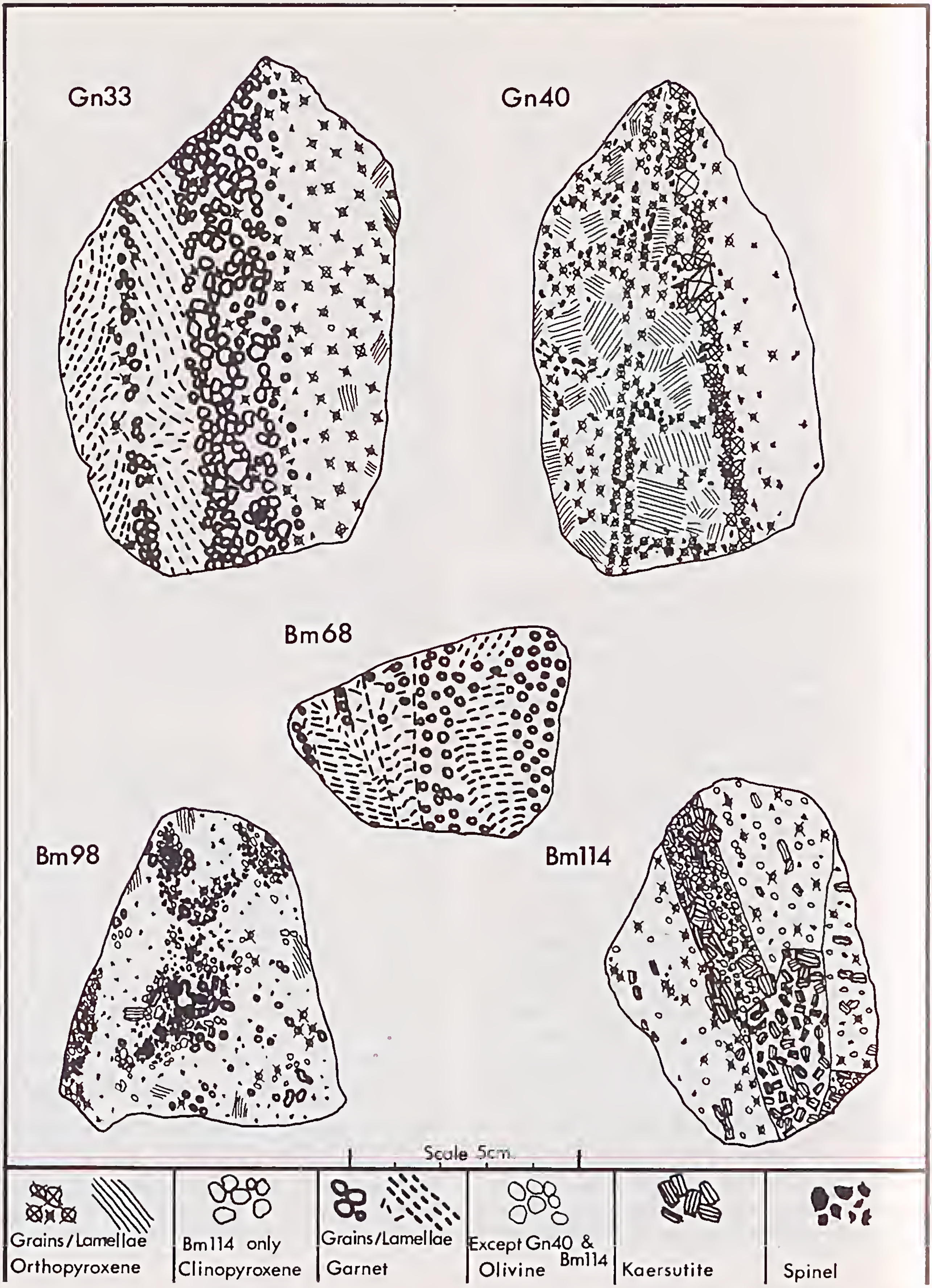


FIG. 3—PYROXENES. Ionic proportions of Ca, Mg, and Fe in pyroxenes from Bullenmerri (blacked-in symbols) compared with those from Mt. Shadwell (S) (Irving 1974a), Delegate (x), Bow Hills (+), Gloucester (ˑ) and Salt Lake Crater (plain). Circles are metaperidotites, squares represent metapyroxenites, triangles = cumulates and rhombs = plagioclase pyroxenites. Tie-lines indicate cpx-opx pairs.



Gn33
Gn40
Bm68
Bm98
Bm114
Scale 5cm.
Grains/Lamellae
Orthopyroxene
Bm114 only
Clinopyroxene
Grains/Lamellae
Garnet
Except Gn40 & Bm114
Olivine
Kaersutite
Spinel

(representing depths of up to 70 km) and at temperatures of 1050 to 1100°C. As to their formation, Irving (1974b) and Beeson & Jackson (1970) favour a magmatic origin, perhaps as cumulates from local pockets of basaltic magma resulting from partial fusion of mantle peridotite, within the mantle. Re-equilibration under cooling conditions may have caused exsolution and recrystallisation with the resultant destruction of cumulus textures. The rocks now seen as nodules may represent a series of parents, liquids and residues connected with several episodes of basic magma generation. Green (1973) showed experimentally that melting garnet peridotite at 25 to 30 kb and 1200 to 1300°C with 2 to 7% water yields liquids of olivine basanite to nephelinite composition.

Peridotites and Pyroxenites

This is a varied group which includes dunites, harzburgites, wehrlites, websterites and clinopyroxenites which often show cumulate textures and sometimes banding of different rock types and grain-sizes. A few nodules contain xenoliths of metaperidotites and rarely metapyroxenites which are well rounded. Xenocrysts from the metamorphic groups may be present either singly or as schlieren. The wehrlites and websterites often have numerous 1 to 5 mm cavities which may be lined with small crystals of hornblende, biotite and rarely magnetite. The lack of metamorphic textures, an absence of Cr diopside and the presence of cavities make these rocks distinct from those of the metamorphic groups. Nodule types unknown elsewhere in Australia include the amphibole peridotite which shows randomly orientated euhedral olivines enclosed by poikiloblasts of deep brown pargasitic kaersutite over 10 cm diameter. Bm 42 has light brownish-green olivine crystals of up to 5 mm, showing multiple twinning and elongation along their c-axes. Other cumulates show olivine in clinopyroxene intercumulus and anhedral clinopyroxene in amphibole intercumulus. Olivine in cumulate nodules ranges from Fo_{65-82}, orthopyroxene is En_{50-75} and clinopyroxene ranges from diopsidic augite to salite; being richer in titania and FeO than the metaperidotite clinopyroxenes (Table 2). Boundaries between rock types within the peridotite-pyroxenite group are curved, irregular or gradational. They reflect in part, junctions between different intercumulus poikiloblast minerals. Nodules having intercumulus feldspars, represented at Mt. Franklin and the Anakies (Wass & Irving 1976) are absent. Most nodules belonging to this group had their origin in the lower crust. This is suggested by

Fig. 4—Petrographic Relationships in some Metapyroxenite and Metaperidotite Nodules

Gn 33 Nodule shows three distinct metapyroxenite rock types arranged in five planar bands. The sequence from left to right (see Table 1) is B2-B1-B2-B1-B3. The B2 garnet pyroxenite shows relics of large pyroxene units which have had orthopyroxene lamellae replaced by garnet. The clinopyroxene has recrystallised to a granular aggregate. B1 is a typical garnet pyroxenite with approximately 55% of pinkish-red garnet in 2 to 5 mm grains. B3 is a hybridised pyroxenite which is garnet-free. A dark green, granular aggregate of aluminous diopsidic-augite (not marked), clear brown orthopyroxene grains and very rare olivine, contains rounded xenocrysts of clinopyroxene with orthopyroxene lamellae.

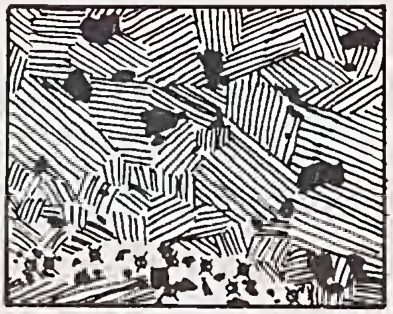
Gn 40 A typical sharp contact between lherzolite (on right) and spinel pyroxenite is emphasised by a prominent zone of orthopyroxene. Large clinopyroxenes have orthopyroxene lamellae. Spinel, Cr diopside, enstatite and greenish-brown kaersutite occur interstitially to the clinopyroxene and also along a healed fracture running obliquely to the lherzolite contact.

Bm 68 Diagram showing an advanced B2 garnet clinopyroxenite with relict clinopyroxene units having garnet lamellae. The pyroxene units are rounded and crumpled. Elsewhere in the specimen, clinopyroxene shows unaltered orthopyroxene lamellae, demonstrating that the mixing of material from different exsolution states occurred at least in part after the development of garnet. Dislocation zones intersecting the clinopyroxene units are lined with small blebs.

Bm 98 This nodule shows significant features of a hybrid garnet pyroxenite with several petrographic types. Kaersutite, spinel and garnet occur in sporadic patches with scattered olivine. Except for the presence of garnet this mineral suite is characteristic of an amphibole lherzolite. Clinopyroxene (unmarked) is a deep green diopside with a lower Cr_2O_3 content than for the Cr diopside common in the lherzolites.

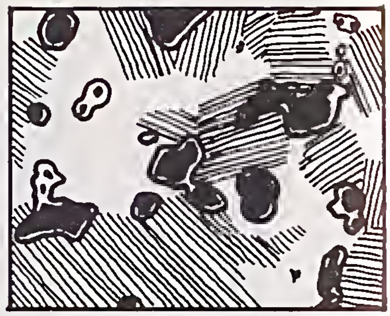
Bm 114 An oblique diagram of a complex kaersutite lherzolite block. Axes of the ovoid kaersutite patches give a marked lineation. Abundant Cr diopside forms a distinct band which includes large kaersutite patches. At the lower left, there is a face of finer granular kaersutite peridotite. This is part of the vein which cuts the general lineation and the Cr diopside band. A complex series of events is indicated by such nodules.

Gn36



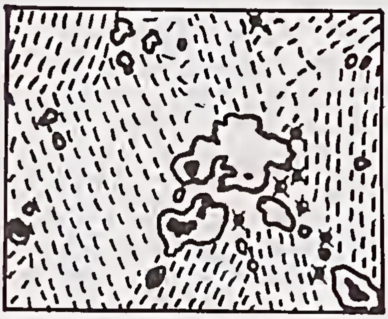
Spinel pyroxenite of Primary Phase.

Bm 67



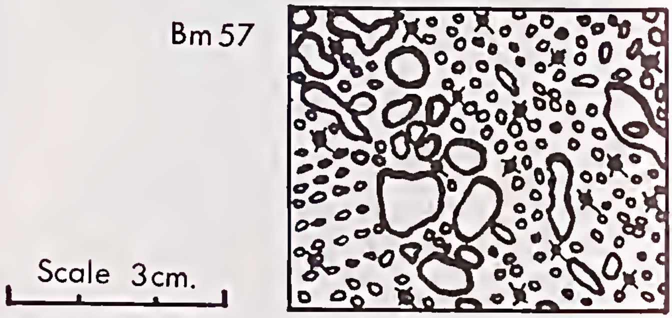
Spinel-garnet pyroxenite of early Garnet Exsolution Phase.

Bm62



Garnet-spinel pyroxenite of advanced Garnet Exsolution Phase.

Bm 57



Garnet Pyroxenite of fully exsolved Garnet Exsolution Phase.

FIG. 5—Stages in the replacement of spinal and orthopyroxene lamellae by garnet. See Fig. 6 for key to symbols.

pyroxenes in comparable nodules from other localities which indicate a pressure range of 7 to 15 kb; e.g. Delegate (Lovering 1969).

HORNBLENDITES AND ESSEXITES

Ultramafic nodules having intrusive textures are common, especially along the south-eastern shores of Bullenmerri, where rounded hornblendite blocks weigh up to 12 kg. Hand specimens consist mainly of black titan-pargasitic kaersutite which is dark brown in thin section. Elongate interlocking crystals may exceed 5 cm and small vesicles are sometimes present. Ilmenite is a frequent accessory often as rough, irregular patches within the amphiboles. Deep brown biotite is sometimes abundant, but plagioclase is absent. The rocks are similar to the 'lherzites' described as veins cutting peridotites in the French Pyrenees by Conquéré (1971). An orange-red euhedral garnet crystal in a small cavity of specimen Bm 5 may be primary. Hornblendites from the Anakies have similar amphiboles, abundant garnet and plagioclase (Irving 1974a). The Bullenmerri blocks sometimes abound in xenolithic materials, producing complex associations. As well as pyroxenites, modified garnet pyroxenites and small patches of granular olivine containing garnet occur. Hornblendites are frequently found as intersecting veins in lherzolite nodules. Wass (1979) considers that these rocks represent magma that crystallised at upper mantle depths. Other veins in some cumulate pyroxenites may represent lower crustal intrusions, in part connected to the magmatic event that led to the maar-producing eruptions.

Coarse-grained mafic to felsic alkali gabbro or essexite blocks up to 2 m across are abundant along the south-eastern shores of Lake Bullenmerri. Although they occur on all the beaches, they are smaller and less common elsewhere. Lithologies vary from relatively fine grained rocks, resembling a theralite, to very coarse with acicular grey plagioclase crystals over 12 cm long. Thin hexagonal plates of ilmenite and acicular black titanaugite are conspicuous, producing an overall grey, decussate appearance. The petrology of these rocks is described by Grayson & Mahony (1910). The blocks are free from veining and xenoliths of any ultramafics. They may be chemically related to the nepheline basanite magmas involved in the volcanism. The essexites were probably torn from alkaline intrusions in the upper crust during eruptions.

Megacrysts

Anhedra of dark brown amphibole up to 4 cm long and related to the hornblendite nodules are abundant in the tuffs. A few crystals have parallel lines of 'pinholes', often having six-sided bores but no set orientation relative to their host's symmetry. Biotite or apatite may have occupied the holes. Rare fragments of clear anorthoclase come from rounded megacrysts up to 5 cm across. The amphiboles developed under hydrous conditions and may indicate that the initial maar eruptions were highly explosive (cf. Vinx & Jung 1977).

ROCK GROUP INTER-RELATIONSHIPS

Relationships within the metapyroxenite group and its contact with the metaperidotites, as observed in nodules are summarised in Fig. 6. This model represents a lower section of a metapyroxenite lenticle within the upper mantle peridotites. The rarity of garnet pyroxenites in nodule suites as a whole, indicates that these lenticles are few and cover restricted areas. The spinel and orthopyroxene replacement series with garnet appears to occur away from peridotite contacts and is thus confined to thicker pyroxenite lenticles. Complex mixing textures appear as the result of subsequent disruptive, partial melting episodes which have resulted in the recrystallisation and Mg-depletion of the olivines and orthopyroxenes. These events may have been connected with the formation of amphibole peridotites, perhaps in association with shearing and diapirism in the upper mantle. The amphibole peridotites may be refractory products of local magma generation within the mantle, under hydrous conditions. These rocks are extremely rare elsewhere and they may be connected to the formation of the garnet metapyroxenites.

CONCLUSIONS

The localities described here provide important and abundant new material from which an evaluation of rock relationships can be made. The assemblage reflects a complex series of events that

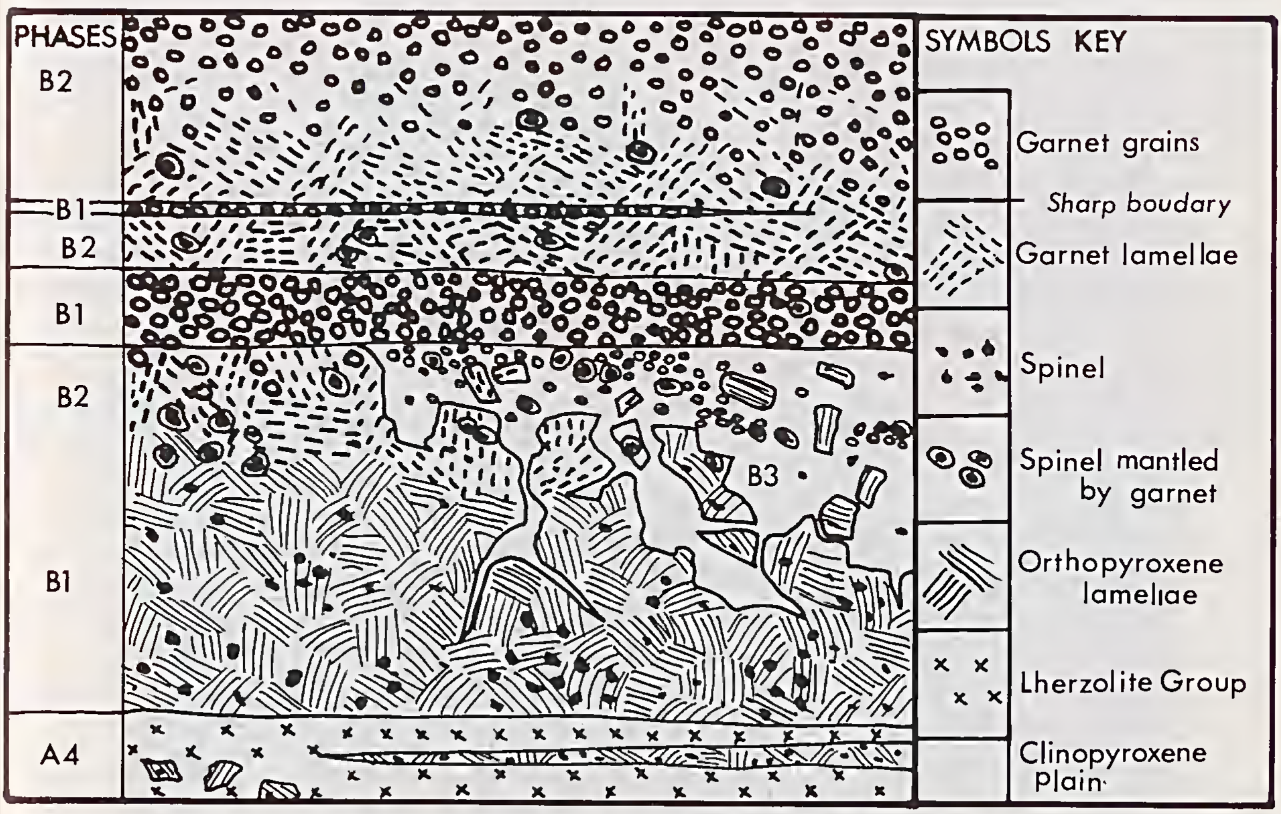


Fig. 6—Phase relationships in the Meta-pyroxenite group.

TABLE 4

ELECTRON MICROPROBE ANALYSES OF AMPHIBOLES AND SPINELS IN NODULES FROM BULLENMERRI AND GNOTUK

	AMPHIBOLES					SPINELS			
PHASE	A4	B3	B3+C1	C1	C2	B1	B2	B3	B3+C1
Specimen	Gn146	Bm106	Bm92	Bm108	Bm83	Gn141	Bm153	Bm55	Bm92
SiO_2	42.95	42.45	42.55	41.84	41.11	0	0	.05	.01
TiO_2	1.87	2.58	4.76	4.60	5.28	.14	.14	.07	1.12
Al_2O_3	15.20	14.87	14.17	14.85	14.06	62.13	62.53	61.75	55.30
FeO*	7.15	8.56	9.82	7.06	9.75	18.94	16.92	14.73	27.46
MnO	.11	.14	.05	.03	.08	.15	.15	.04	.07
MgO	15.99	14.73	12.73	14.83	13.10	17.46	18.06	20.28	15.03
CaO	10.98	10.69	10.17	10.50	10.10	.02	.02	0	.02
Na_2O	3.43	2.87	2.83	3.11	2.86	.02	0	.05	.03
K_2O	.26	1.69	1.49	1.52	2.28	0	0	.02	.01
Cr_2O_3	.08	.10	0	.12	.02	1.10	.90	2.69	.48
NiO	.12	.04	.08	0	.05	.26	.29	.27	.15
BaO	.05	0	0	0	0	0	.08	0	.01
Total	98.19	98.72	98.65	98.46	98.69	100.23	99.11	99.95	99.71
Ion%									
Mg	76.3	70.7	61.7	70.3	61.7	61.5	65.0	69.3	49.2
Fe	19.2	23.0	26.7	18.7	25.8	37.5	34.2	28.3	50.4
Ti	4.5	6.3	11.6	11.0	12.5	—	—	—	—
Cr	—	—	—	—	—	1.0	0.8	2.4	0.4

* Total iron as FeO (Fe^{++}).

have left textural records of shearing, hybridisation and partial melting. Certain significant events may be recognised in the nodules, although much clarification is needed, based on new data such as Nd-Sm ratios.

Important events included:

1. Formation or major reconstitution of the normal Cr diopside—spinel lherzolites between 2 and 2.5×10^9 years ago is suggested on isotopic evidence (Cooper & Green 1969) from xenoliths at Mt. Leura, 1 km east of Lake Bullenmerri. Recrystallisation and partial melting eposides may have generated pyroxenite magmas that formed concordant bodies in the metaperidotites.

2. Pyroxenites and metaperidotites underwent a major thermal event around 650×10^6 years ago (Burwell 1975). The resultant metapyroxenites may have yielded the garnet-bearing rocks by exsolution reactions. Shearing and hybridisation accompanied the generation of further pyroxenite melts at upper mantle levels, which intruded the metamorphic hosts, forming cross-cutting veins. Larger bodies of melt developed clinopyroxene and olivine cumulates.

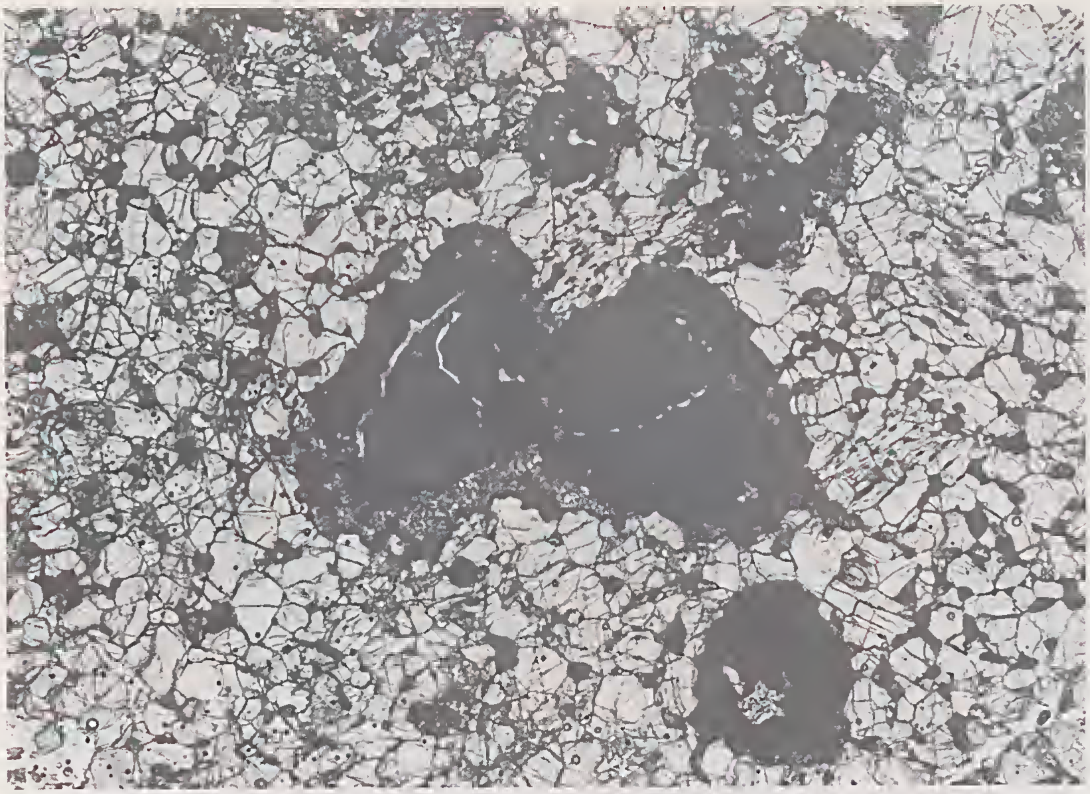
3. Hornblendite magma intruded upper mantle rocks. The date of this event is conjectural, but one possibility is that it occurred during the Mesozoic. Hydrous magmas which could be

PLATE 13

Fig. 1—Photomicrograph of spinel—garnet pyroxenite (AM6814) from Bullenmerri, showing large, primary spinels mantled by kelyphite alteration after garnet. Small blebs of garnet, exsolved from the pyroxenes, occur both interstitially to and along planes in clinopyroxenes. High-pressure recrystallisation indicated by triple-point grain boundaries.

Fig. 2—Photomicrograph of garnet pyroxenite (AM6810) from Bullenmerri. Large, primary clinopyroxene with garnet lamellae exsolved after orthopyroxene, on left hand side. Large, ? primary garnet on lower right shows typical fracturing and black alteration rims. Also small interstitial grains of garnet amongst pyroxenes.

Both Plates approx. X 100. Photography by David Barnes.



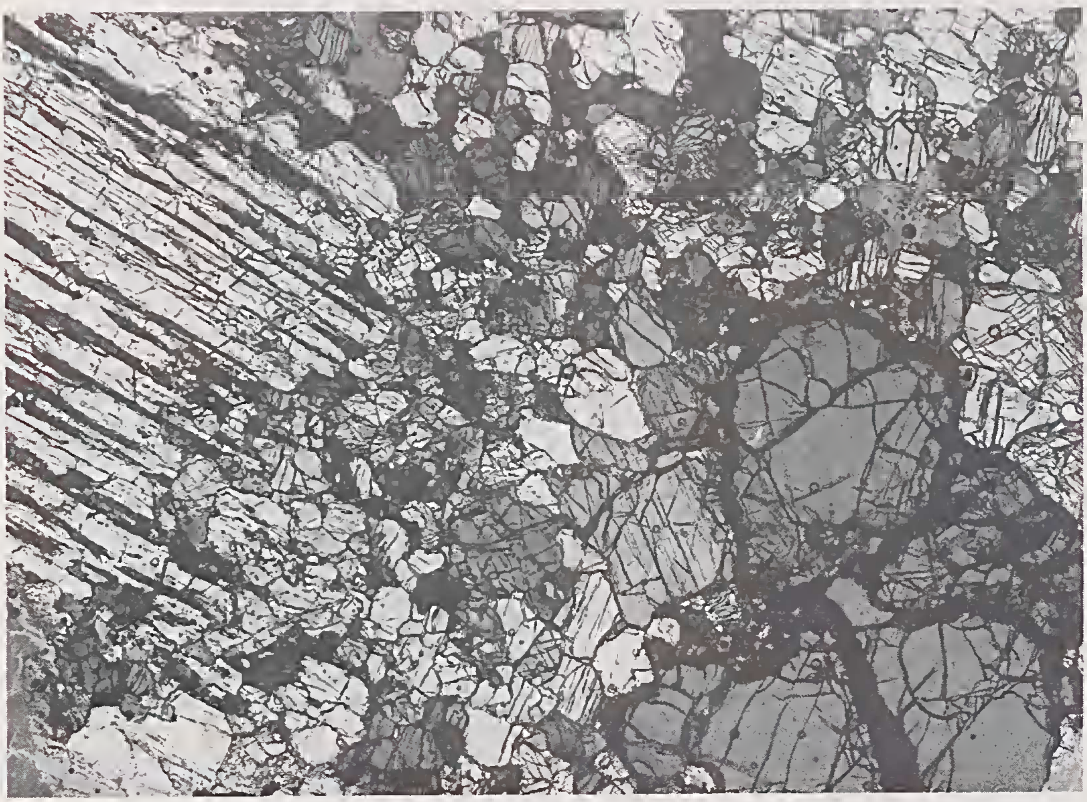


PLATE 13

related to the hornblendites produced volcanism in the Meredith area dated at 163×10^6 years (Day *et al.* 1979) and kaersutite megacrysts occur in Jurassic volcanics of the Dundas Tableland (Fullarton & Tattam 1976).

4. The upper mantle was locally disrupted by magma diapirs which culminated in the Newer Volcanic Episode. Xenoliths were erupted with magma during the initial maar-producing activity at Lakes Bullenmerri and Gnotuk. Crustal blocks of essexite were included.

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